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Spontaneous spin polarization in a quantum wire

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Firstly the miraculous "0.7 structure" was seen in the experiments with quantum wires (QWRs) in 1996 [1]. There was registered the pronounced additional step of a quantum wire conductance quantization at the level 0.7 of a conductance quantum $G_0 = 2e^2/\hbar$. A bit later an apparent deviation from a conductance quantum $G_0 = 2e^2/\hbar$ was also observed in the most perfect for today long QWRs fabricated by cleaved overgrowth of GaAs/AlGaAs quantum well heterostructures [2]. Even a decrease up to 50% was registered for 20 μ wire. Worth mentioning that the effect was present for multiple quantization steps visible in the experiment. Recently a novel observation of the 0.7 structure was made in quantum wires manufactured by split-gate technology [3]. The authors saw again an additional step of quantization at the level $0.7 \cdot 2e^2/\hbar$. The fact that quite different structures revealed the same effect pointed out to its fundamental origin.

For a while there was no adequate explanation consistent with all available experimental data. Attempts to apply the spin and spinless Luttinger liquid theories seemed the most appropriate to unravel the problem. Indeed, these theories gave the corrections to QWR conductance caused by Coulomb interaction between electrons [4]:

$$G = G_0(1 + V(0)/\pi v_F)^{-1/2} \qquad (1)$$

where $V(0)$ represents the Fourier transform $V(q)$ of the real space interaction potential between electrons for the transfer momentum q equal to zero, v_F is the Fermi velocity. However, these corrections have monotonic dependence on the Fermi energy that contradicts with abrupt transition to common integer steps of conductance quantum with rising a gate voltage observed in the experiment [3] and flat plateaus observed in [2].

When a disorder was involved [5] this also gave rise to an obvious decrease of the conductance but dependent on the electron density in the wire. The calculations fulfilled for realistic QWR wall roughness also revealed a strong dependence of scattering rate on the Fermi energy and subband number [6]. Thus such a scattering can not be at all a feasible reason of conductance deviation because it do not accord with observed flat plateaus (within 5%) and conductance steps of equal height [2].

Moreover, the latest experiments discovered an obvious connection of the "0.7 structure" with spin polarization of electrons in a QWR. They saw a smooth transition of the "0.7 structure" for zero magnetic field to the "0.5 structure" when a magnetic field was going up [3]. This experimental evidence crucially sustains the hypothesis of spontaneous spin polarization of electrons in a QWR was beforehand put forward in [7].

Here we argue that the strong deviation from conductance quantum is caused just by a spontaneous spin polarization due to exchange interaction between electrons in a QWR.

As for Coulomb interaction, it can be put into consideration in an audible self-consistent way. However, a realistic Coulomb potential in a QWR should be taken into account [8]. Surely, the electrostatic potential induced by internal electrons in a QWR can even blocade

the wire conductance. But we adhere to the experimental conditions when the wire was quite penetrable for electrons and electrostatic potential can not influence on the linear response to infinitesimal bias applied to the wire.

We assume that exchange energy is small compared with kinetic energy so that pair interaction between electrons is efficient approximation. Suppose that two electrons move across QWR in the same direction (left or right moving fields) with sufficiently small longitudinal momentum difference $\hbar \Delta k$ so that

$$\hbar \Delta k < \hbar / \lambda \tag{2}$$

where λ is an effective screening length ($\lambda < L$) and L is a wire length. These electrons possess exchange energy almost as great as Coulomb energy, i.e.

$$(e^2 / \kappa L) \ln(\lambda / d). \tag{3}$$

Here d is a QWR diameter. In our calculations the conventional Coulomb potential $V(x) = 1/\kappa x$ was cut off for distances x smaller than d. For greater momentum mismatch exchange integrals involve fast oscillating functions and tend to zero. A sign of exchange energy depends on the spin configuration. If electrons have an antisymmetric spin configuration (total spin equals unity) then their space wave function is symmetric and the sign of exchange energy is positive, i.e. the same as that of Coulomb energy. Otherwise, when a total spin equals zero, the exchange energy is negative and reduces total energy of electron system.

It was found out that due to exchange interaction the ground state ($T = 0$) corresponding to the minimum of the total energy (including kinetic one) can be that of predominant symmetrical spin configuration for electrons near the Fermi level, i.e. spin polarized. The condition of the cross-over from conventional unpolarized state to polarized one is as follows

$$\frac{\pi a_B k_F}{4 \ln(\lambda / d)} < 1 \tag{4}$$

where k_F is the Fermi electron wave vector and $a_B = \hbar^2 \kappa / me^2$ is a Bohr radius. It should be noted that much higher Fermi energies obey the above condition than that obeying the condition of 1D Wigner crystallization derived in [12]. Although these conditions differ only by coefficients and arguments in logarithmic function this difference is essential. Once the condition (4) is met the polarized phase arises in the energy interval under the Fermi level

$$\delta \epsilon = (e^2 / \kappa \lambda) \ln(\lambda / d). \tag{5}$$

The magnitude of $\delta \epsilon$ equals the exchange energy per one Fermi electron. Worth mentioning that it does not depend upon Fermi energy of electrons in any subband of a QWR. This is in a good qualitative agreement with the experimental evidence for conductance corrections to be insensitive to the Fermi energy [2].

In a polarized phase the density of states of electrons adjacent to the Fermi level much decreases although at the same moment energy corrections (consequently the corrections of Fermi velocity v_F) are rather small. We obtained the relative decrease of the electron density of states in the energy interval $\delta \epsilon$ under the Fermi level as follows:

$$\frac{1}{\pi a_B k_F} \ln(\lambda / d). \tag{6}$$

According to inequality (4) the decrease of density of states cannot be less than 1/4 in spin polarized phase. The "diluted" density of states results in corresponding decrease of

a conductance. However, as the parameter (6) is not small a non-perturbation approach should be devevoped to get a precise number.

Our estimations show that the condition of a cross-over (4) to polarized phase is valid even for top Fermi energies attained in the experiment [2] (unlike to that in [3]). We accepted for evaluations a screening length λ equal to a several timed distance from the QWR to the nearest gate electrode and the wire diameter d consistent with subband spacing (20 meV) pointed out there. Then we gained $\delta\epsilon$ exceeding kT (T about 1 K). When the temperature is rising the polarized phase is smeared and the conductance quantum restates. This explains the abnormal temperature dependence of the QWR conductance seen in the experiment. When the bias V exceeds the value of $\delta\epsilon/e$ "undiluted" electrons, i.e. outside the polarized layer, are involved in the conductance and thus a conductance quantum restates too.

To be consistent with over-all experimental data [2] a wire length should be introduced in the theory. The experiment revealed a quite weak dependence of the conductance deviation on the wire length, at least, sub-linear one. The conductance deviation was only doubled while the wire length varied from $1\,\mu$ to $20\,\mu$. Two possibilities look plausible. The first one is that in the experimental structure the wire diameter diminishes as wire lengthens. An indirect allusion to this very dependence was that the less negative gate voltage pinched off a longer wire. The second possibility is an interaction of a wire with leads which partially ruins polarized phase in the pre-contact region. Although the presence of the leads was already modeled in [9–11] this consideration looks quite deficient yet.

In conclusion, an existence of predominant symmetrical spin configuration (spin polarized phase) and "diluted" density of states under the Fermi level in the quantum wire is considered. The reduction of quantum wire conductance is in agreement with recent experimental data.

Acknowledgments

References

[1]   K. J. Thomas *et al*. *Phys. Rev. Lett.* **77**, 135 (1996); *Phys. Rev. B* **58**, 4846 (1998).

[2]   A. Yacoby, H. L. Stormer, N. S. Wingreen, L. N. Pfeifer, K. W. Baldwin, K. W. West, *Phys. Rev. Lett.* **77**, 4612 (1996).

[3]   C.-T. Liang, M. Y. Simmons, C. G. Smith, G. H. Kim, D. A. Ritchi and M. Pepper http://xxx.lanl.gov/abs/cond-mat/9907379.

[4]   W. Apel and T. M. Rice, *Phys. Rev. B* **26**, 7063–65 (1982).

[5]   D. L. Maslov, *Phys. Rev. B* **52**, R14 368 (1995).

[6]   V. A. Fedirko and V. V. V'yurkov, *Russian Microelectronics* **26**, 216 (1997).

[7]   V. V'yurkov, V. Fedirko and L. Fedichkin, *Phys. Low-Dim. Struct.* N 3/4, 200–26 (1999).

[8]   V. A. Sablikov and B. S. Shchamkhalova, *Phys. Rev. B* **58**, 13 847 (1998).

[9]   D. L. Maslov and M. Stone, *Phys. Rev. B* **52**, R5539–42 (1995).

[10]   V. V. Ponomarenko, *Phys. Rev B* **52**, R8666–67 (1995).

[11]   I. Safi and H. J. Schulz, *Phys. Rev. B* **52**, R17 040–43 (1995).

[12]   V. V'yurkov and L. Fedichkin, *Phys. Low-Dim. Struct.* N 12, 277–80 (1995).